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Analyzing Conformance Monitoring in Air Traffic Control Using Fault Detection Approaches & Operational Data

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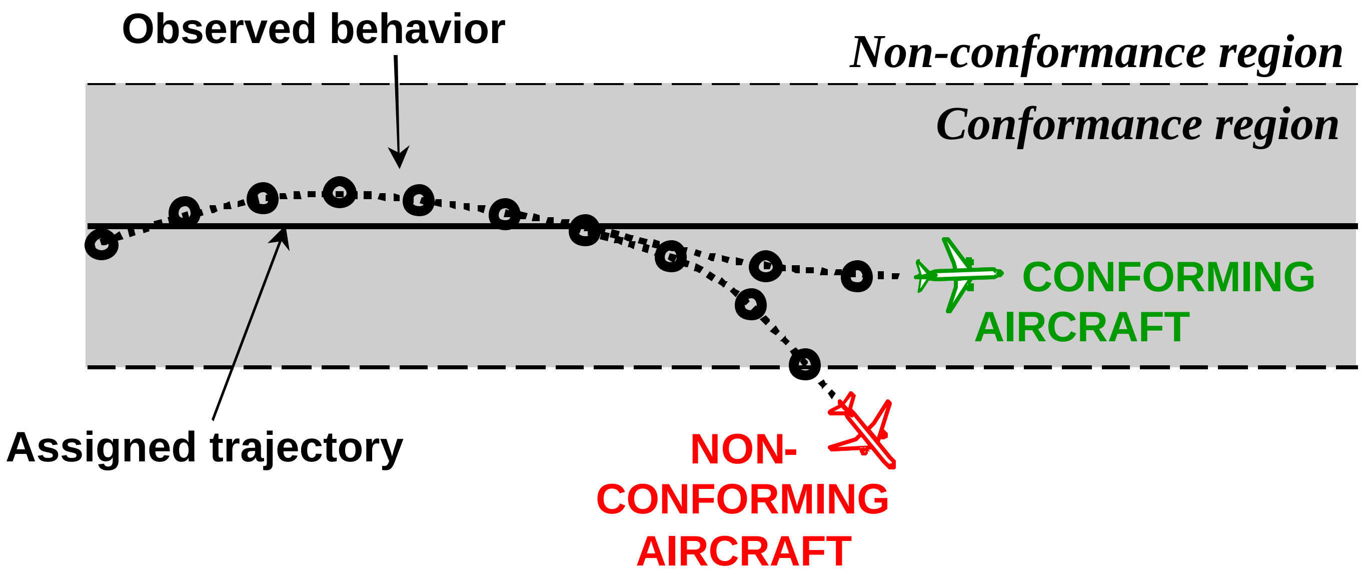
CONFORMANCE MONITORING IN ATC

- **Conformance monitoring is critical function in ATC to ensure aircraft adhere to their assigned trajectories**
- **Essential to many ATC functions**
  - Aircraft separation
  - Security considerations (increased post-9/11)
  - Efficiency of traffic flows



MOTIVATION FOR RESEARCH

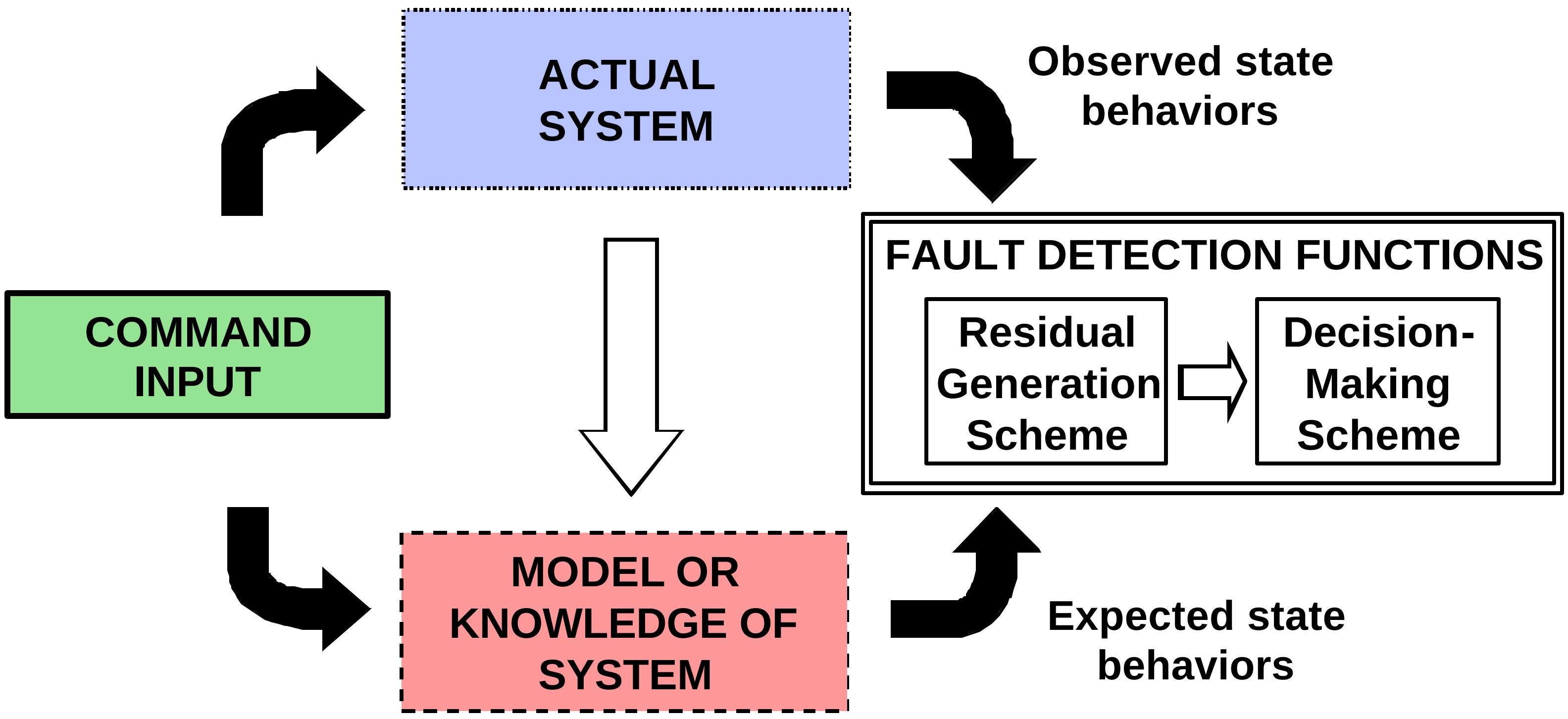
- **Better conformance monitoring may enable future ATC system performance improvement**

- **Advanced automation and surveillance systems may enable more effective conformance monitoring to be undertaken**
  - ☐ Higher accuracy/update rate surveillance systems
  - ☐ Datalink of states *from* aircraft
    - o Automatic Dependent Surveillance-Broadcast (ADS-B)
  - ☐ Communication of clearances *to* aircraft
    - o Controller-Pilot Datalink Communication (CPDLC)

- **Need to develop analysis techniques to support development of more effective conformance monitoring systems for ATC**

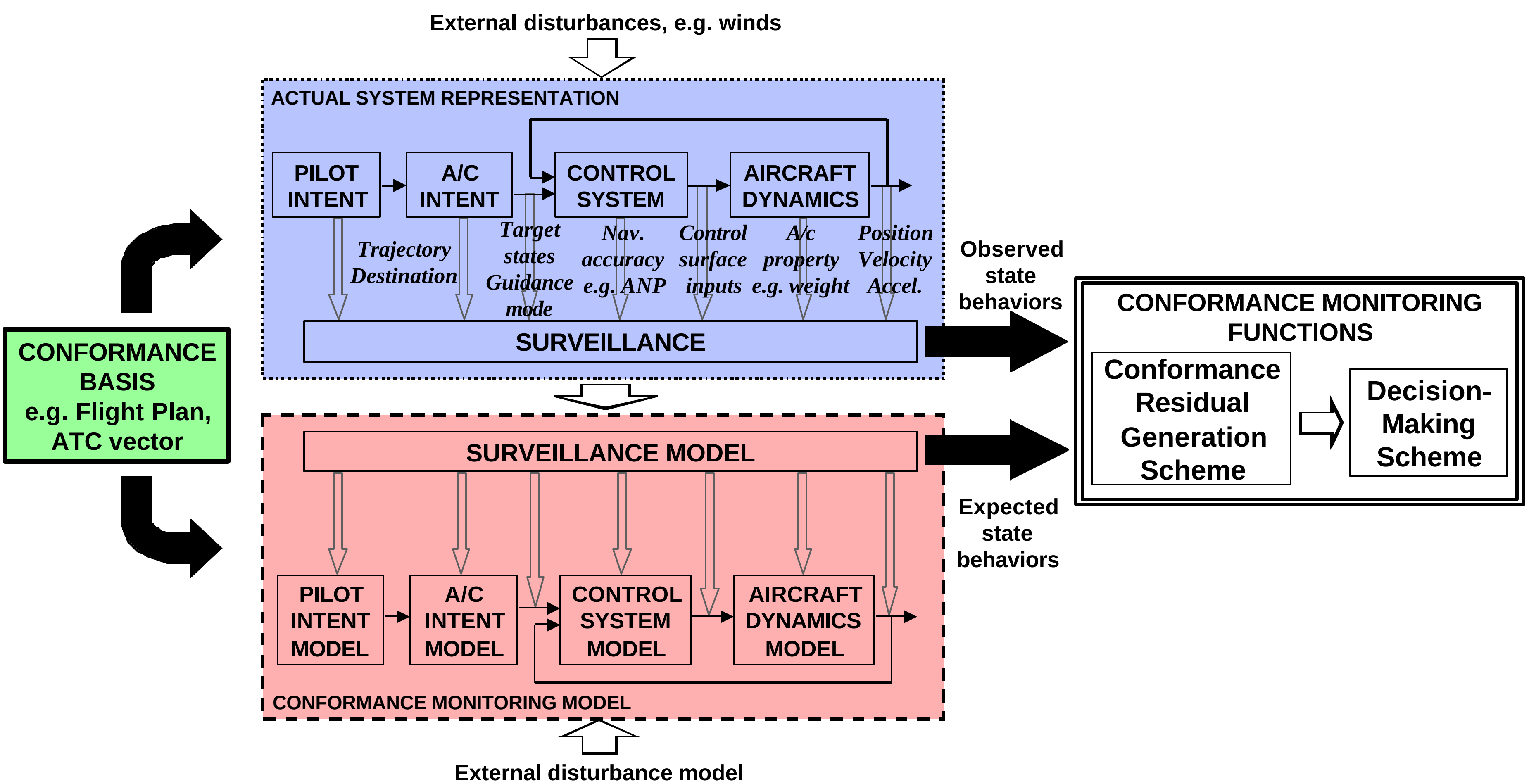
CORE RESEARCH APPROACH

- **Conformance Monitoring as Fault Detection**
  - Pose conformance monitoring as a Fault Detection problem where an aircraft deviation is considered a "fault" in the ATC system needing to be detected
  - Existing Fault Detection techniques can then be used for this application

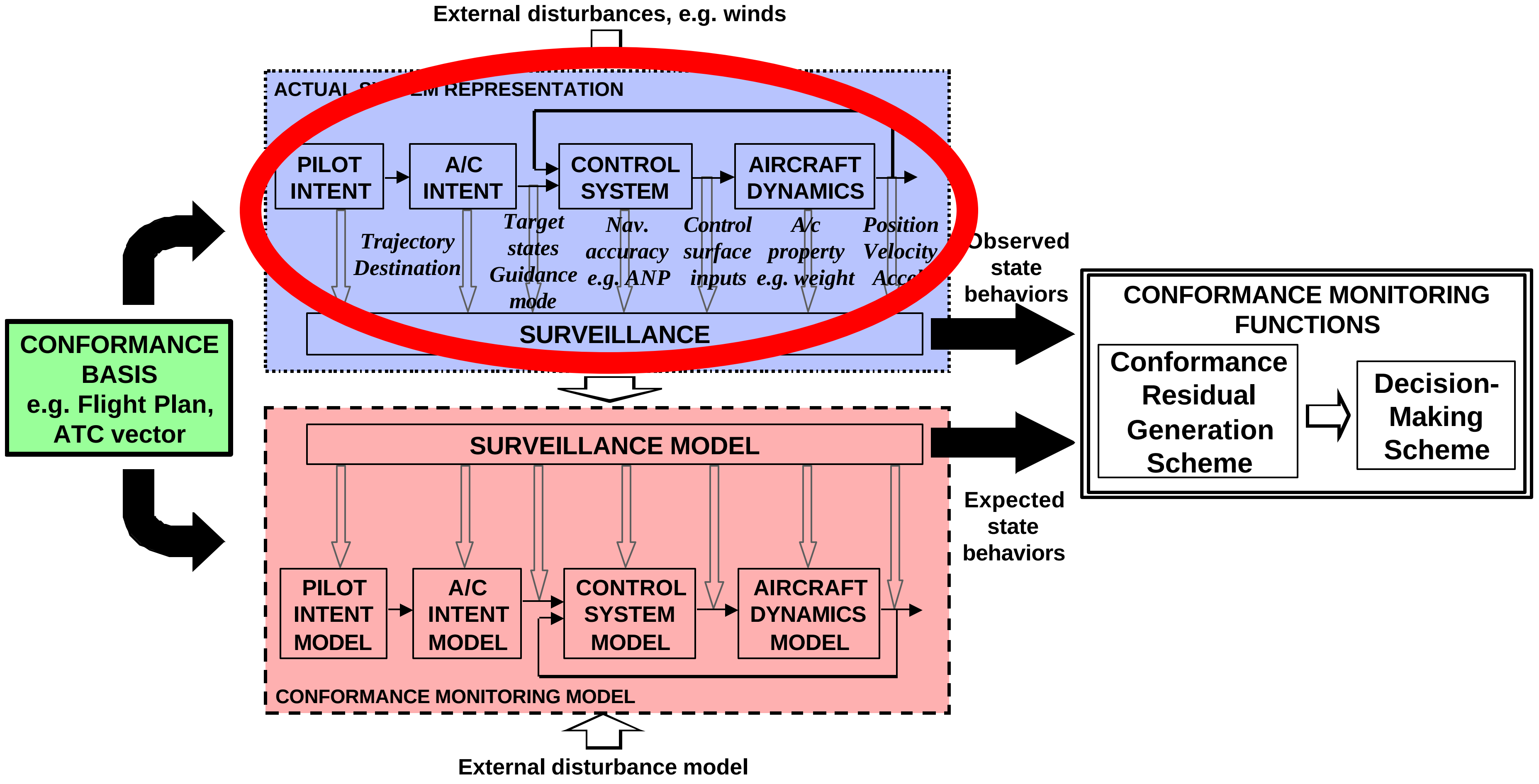


CONFORMANCE MONITORING ANALYSIS FRAMEWORK

- **General fault detection framework tailored for conformance monitoring application:**

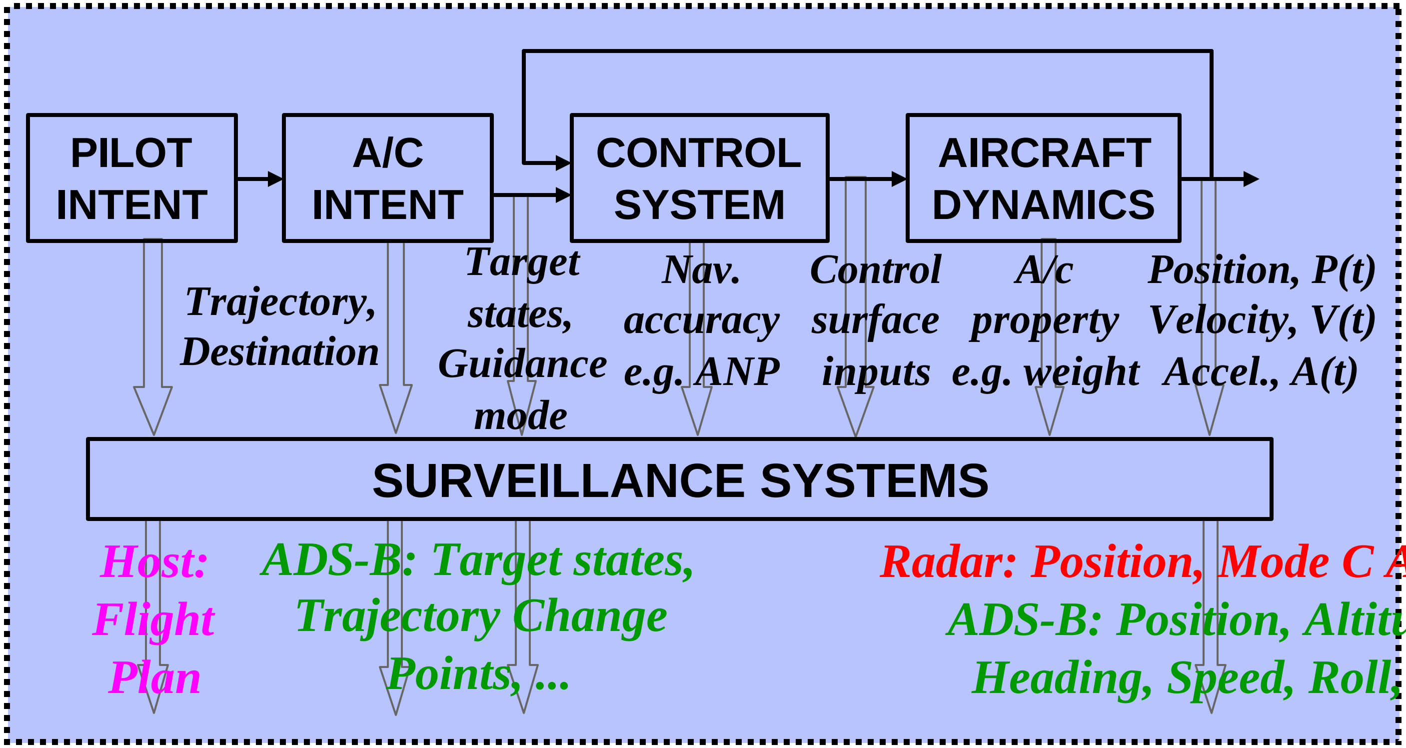


ACTUAL SYSTEM REPRESENTATION

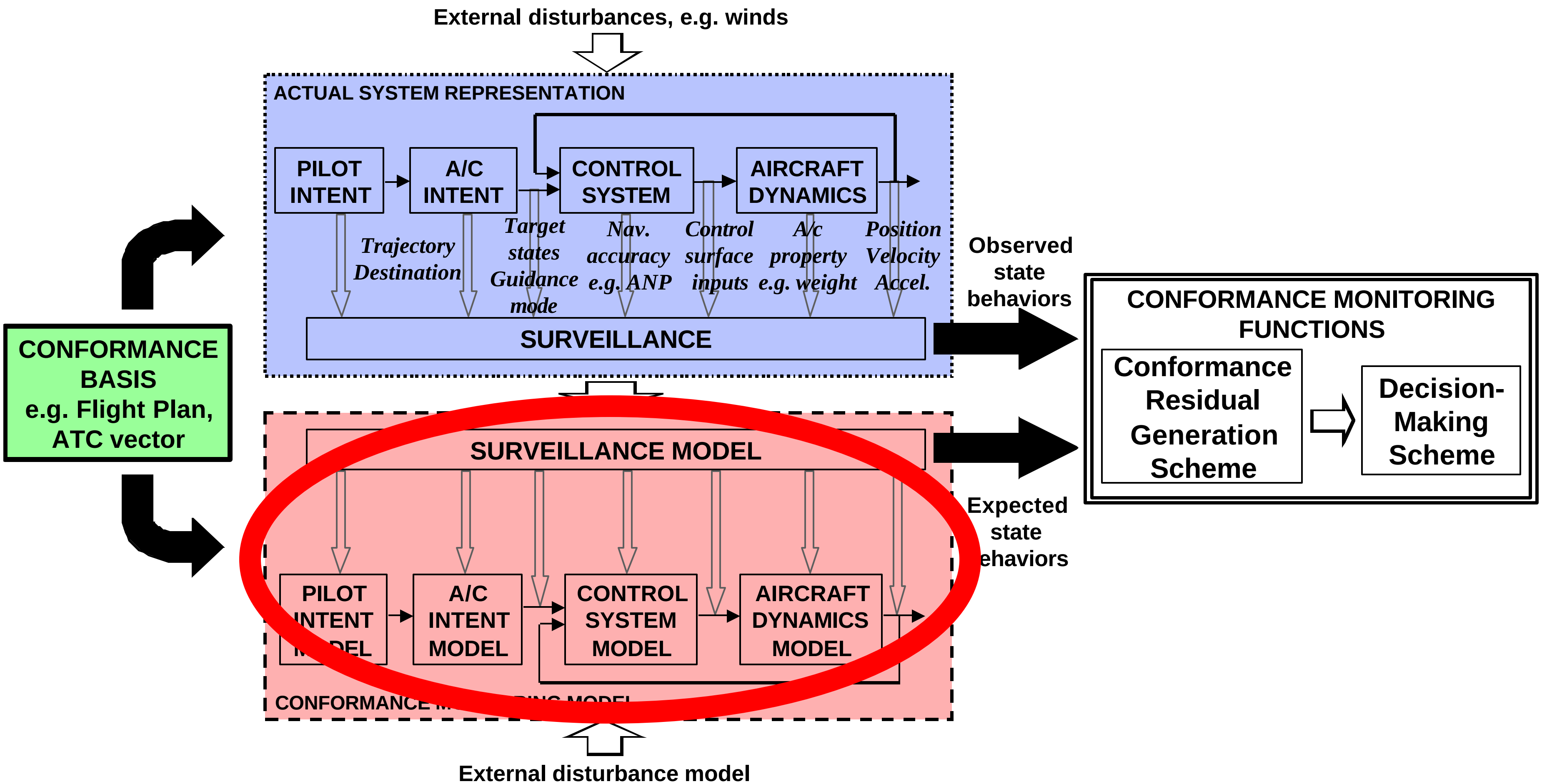


ACTUAL SYSTEM REPRESENTATION

- **Key elements involved in executing the Conformance Basis**
- **Feedback representation of control system supplemented with “intent” components to capture future behavior**
- **Can represent different surveillance environments**

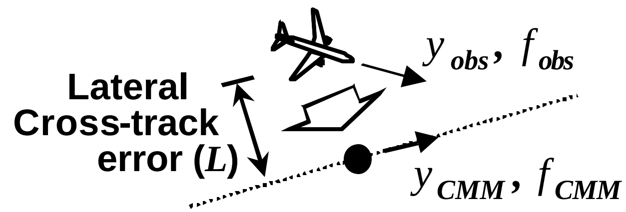


CONFORMANCE MONITORING MODEL (CMM)

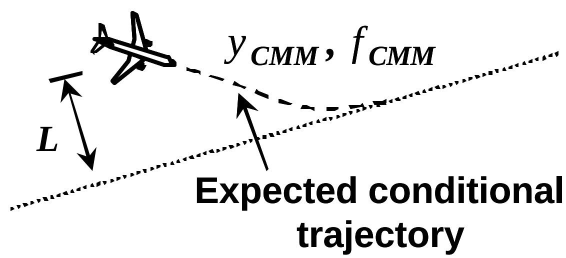


CONFORMANCE MONITORING MODEL (CMM)

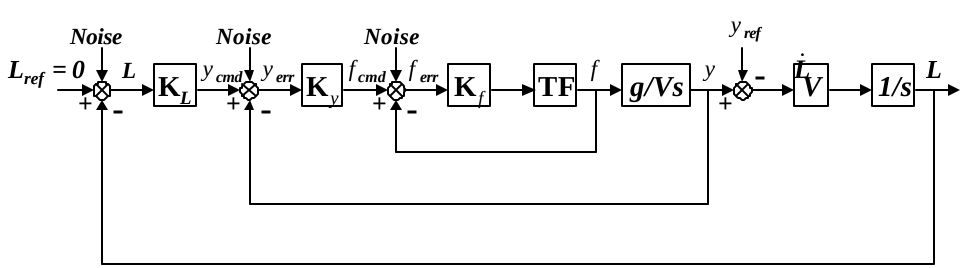
- **Conformance Monitoring Model generates expected state values**
  - Shown with elements mirroring those in Actual System Representation
- **Can contain varying degrees of sophistication, for example:**
  - Dictated solely by Conformance Basis



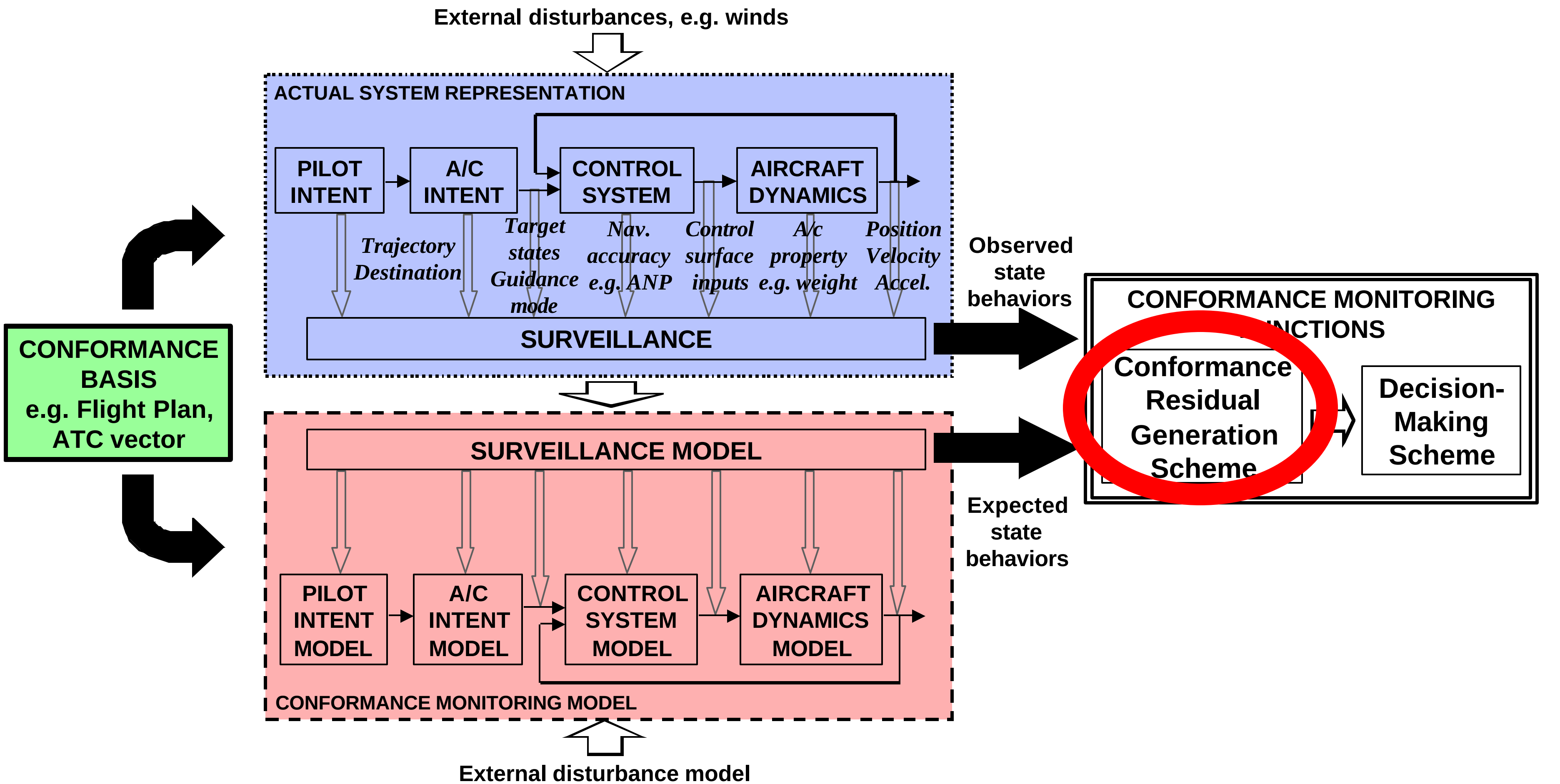
  - Incorporating knowledge or heuristics of behavior at different locations



  - Explicit dynamic model of aircraft behavior



CONFORMANCE RESIDUAL GENERATION



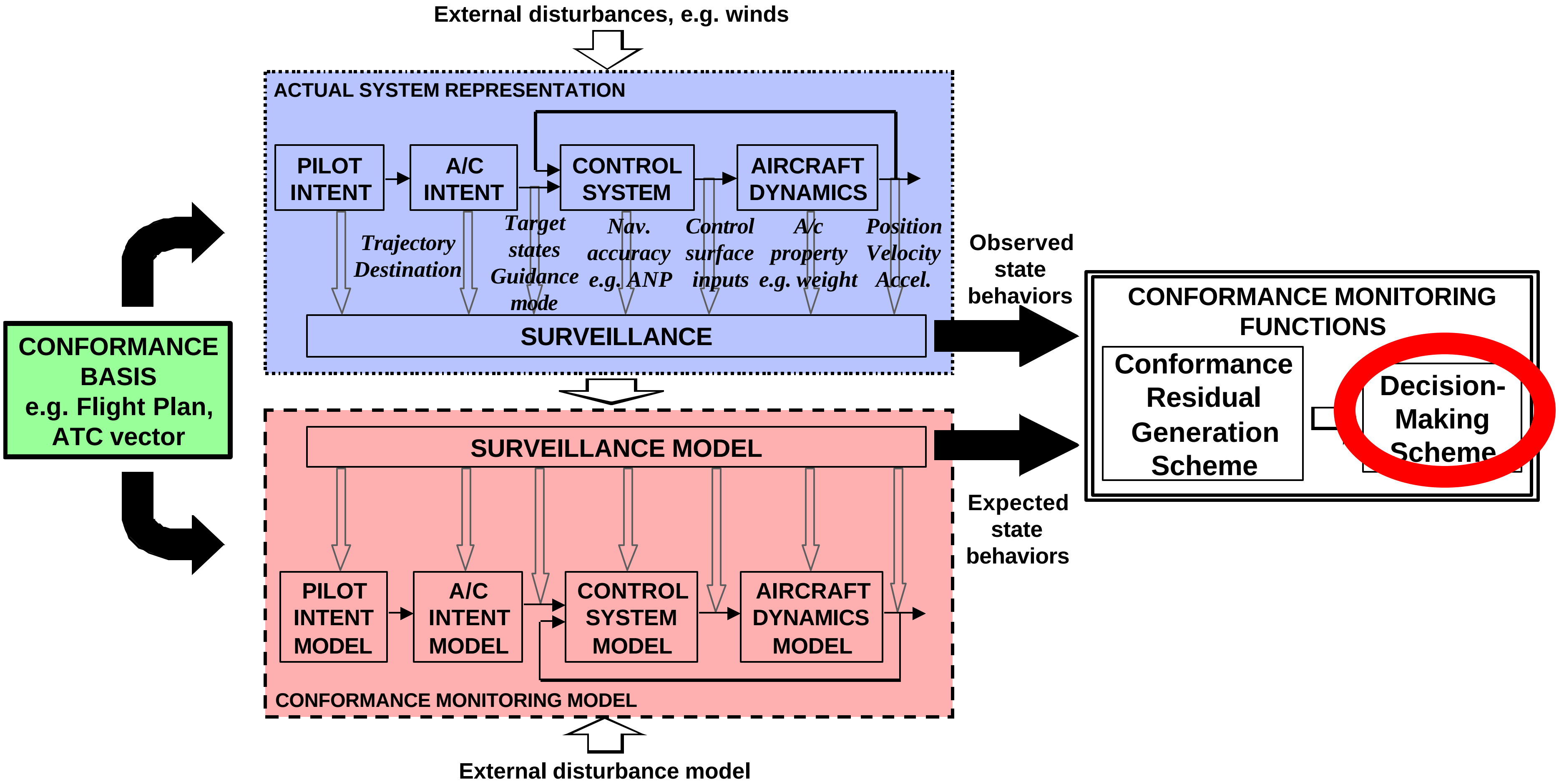
CONFORMANCE RESIDUAL GENERATION

- **Conformance Residual quantifies the difference between the observed states available through surveillance systems and the expected behavior generated from the CMM**

- **Challenge is to generate a residual that effectively describes whether the aircraft is behaving in a conforming fashion or not**

- **Many approaches can be employed, for example:**
  - ☐ Scalar functions of the form: $CR_{scalar} = \sum k_x \cdot f(x_{obs} - x_{CMM})$
    - o Simple, but can mask behaviors in multivariable residuals
  - ☐ Vector forms where components defined by residuals on various states
    - o More complex, but reveals separate state behaviors in multivariable residuals

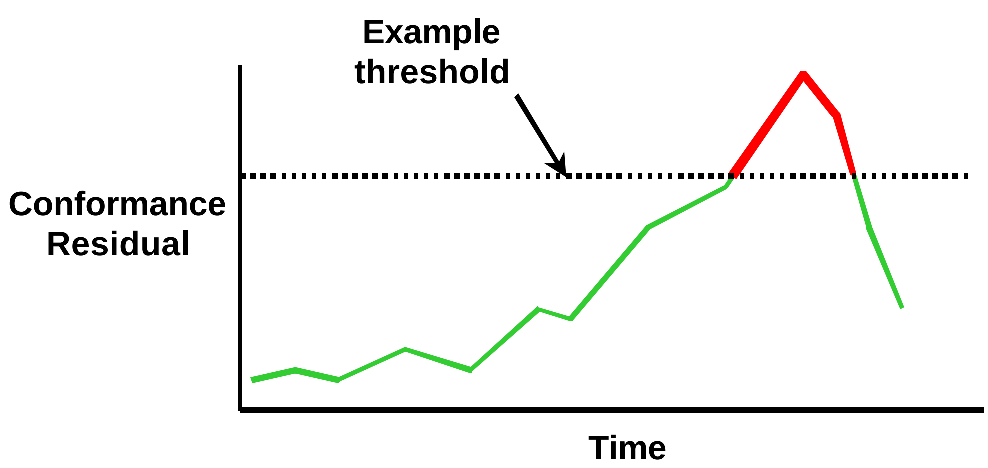
DECISION-MAKING



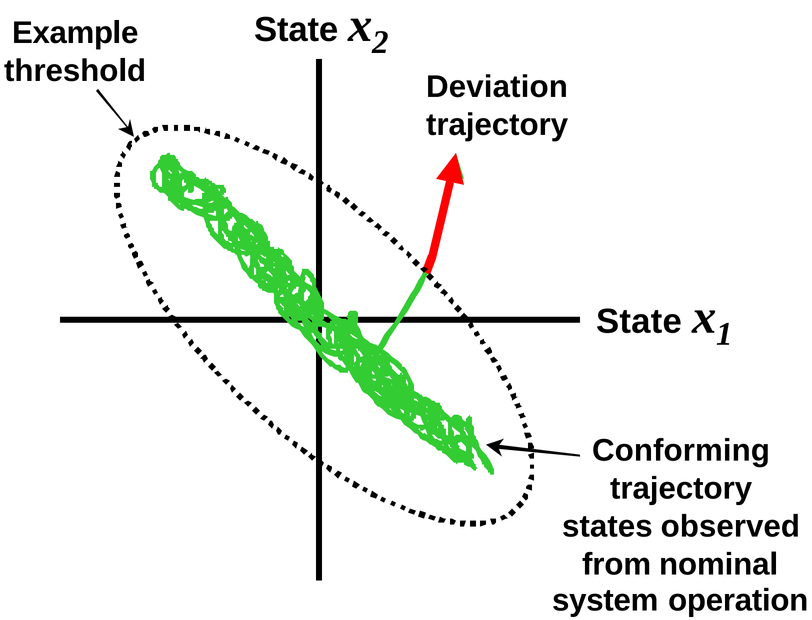
DECISION-MAKING

- Consider evidence in Conformance Residual to make best determination of conformance status of aircraft

- Simple approach is to use threshold on Conformance Residual



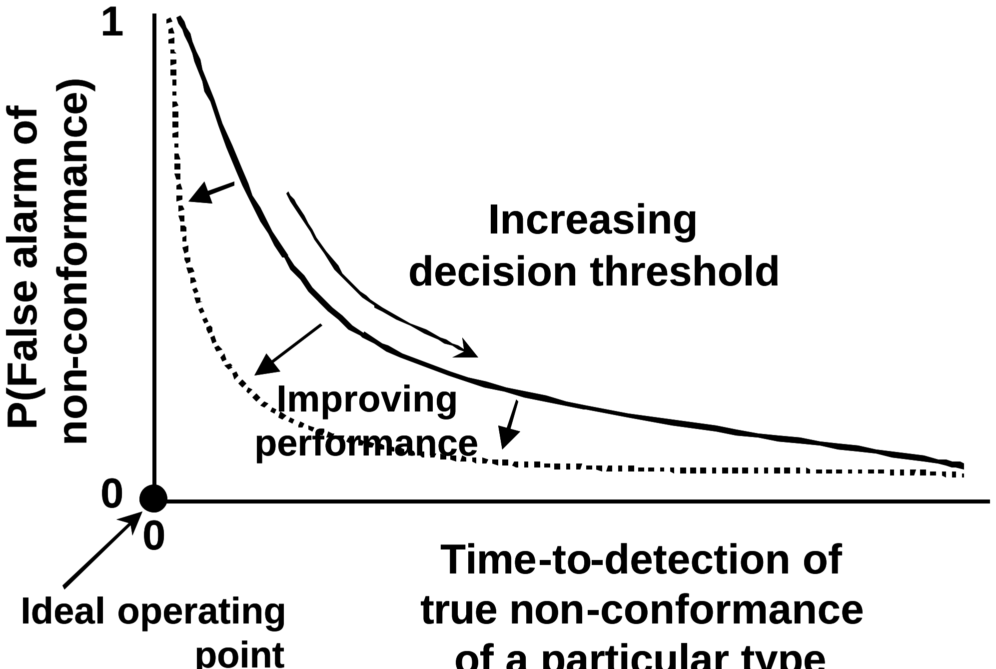
Scalar residual



Vector residual

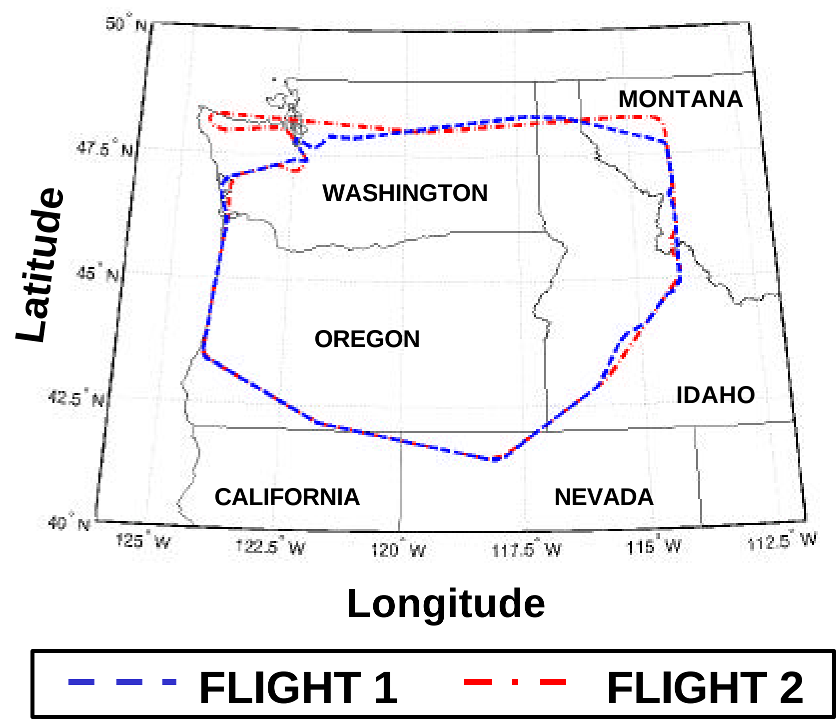
DECISION-MAKING PERFORMANCE MEASURES

- **Threshold placement affects various performance measures**
  - Time-To-Detection
  - False Alarms
  - Maximum Conformance Residual
- **Targets on performance measures define acceptable threshold placement**



FRAMEWORK EVALUATION USING OPERATIONAL DATA

- **Boeing 737-400 test aircraft**
  - ☐ Collaboration with Boeing ATM
  - ☐ Two test flights over NW USA
  - ☐ Experimental configuration not representative of production model
- **Archived ARINC 429 databus states**
  - ☐ Latitude/longitude (IRU & GPS)
  - ☐ Altitude (barometric & GPS)
  - ☐ Heading, roll, pitch angles
  - ☐ Speeds
  - ☐ Selected FMS states (desired track, distance-to-go, bearing-to-waypoint)
- **Archived FAA ground information**
  - ☐ Radar latitude/longitude
  - ☐ Radar-derived heading & speed
  - ☐ Mode C transponder altitude
  - ☐ Assigned altitude
  - ☐ Flight plan route



ANALYSIS SCENARIOS

- Several intentional lateral and vertical flight deviations conducted with agreement of ATC
- Provide opportunity to test implementation of framework under various operational & surveillance environments

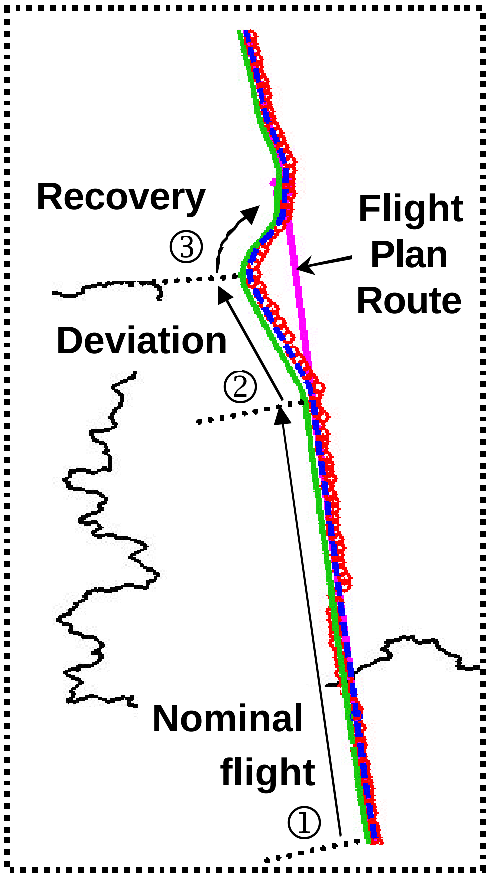
SURVEILLANCE ENVIRONMENT

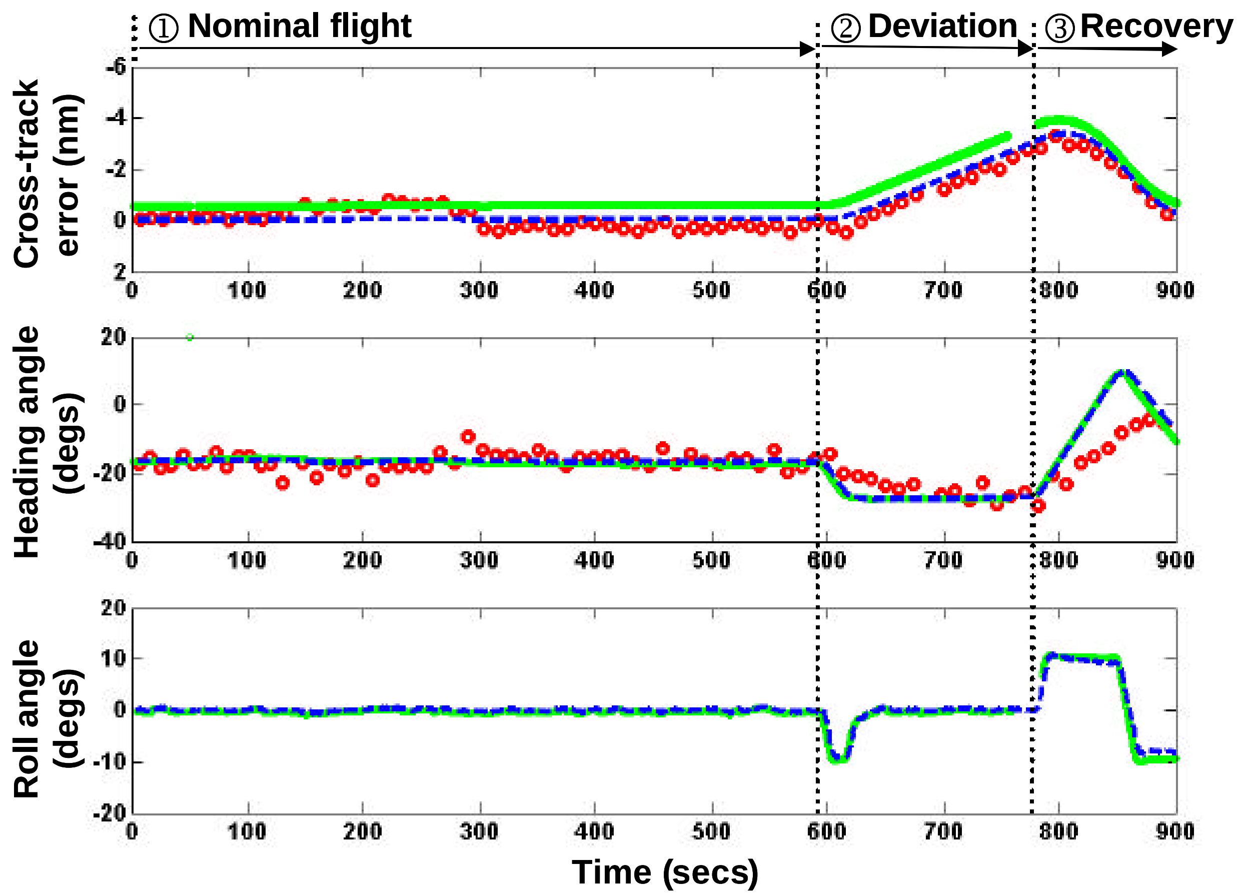
OPERATIONAL ENVIRONMENT

	Aircraft-based data	Radar-based data
Lateral	• Straight flight • Transitioning flight	• Straight flight • Transitioning flight
Vertical	• Level flight • Transitioning flight	• Level flight • Transitioning flight

LATERAL CONFORMANCE MONITORING DURING STRAIGHT FLIGHT

LATERAL DEVIATION TEST SCENARIO





Databus data (0.1 sec) GPS data (1 sec) Radar data (12 sec)

EXAMPLE FORMS OF FRAMEWORK ELEMENTS

- **Conformance Basis**
  - Host Flight Plan route
- **Conformance Monitoring Model**
  - Simple form dictated by Conformance Basis
  - L_{CMM} = 0 nm, ψ_{CMM} = flight plan leg course corrected for wind, ϕ_{CMM} = 0°
- **Conformance Residual**
  - Normalized absolute function scalar, $CR = \dfrac{\sum WF_x \left| x_{obs} - x_{CMM} \right|}{n}$
  - Weighting factors, WF_x used to normalize each state component, x to acceptable conforming behavior (analogous to Required Navigation Performance (RNP) philosophy) or to reflect each state's relative importance
- **Decision-making**
  - Threshold-based

AIRCRAFT/GROUND BASED CONFORMANCE MONITORING COMPARISON

- **State combinations considered for aircraft and ground data:**
  - ☐ Lateral cross-track position (L) only
  - ☐ Lateral cross-track position (L) & heading (y)
  - ☐ Lateral cross-track position (L), heading (y) and roll (f) [aircraft data only]
- **Conformance Residuals generated for aircraft and ground data:**

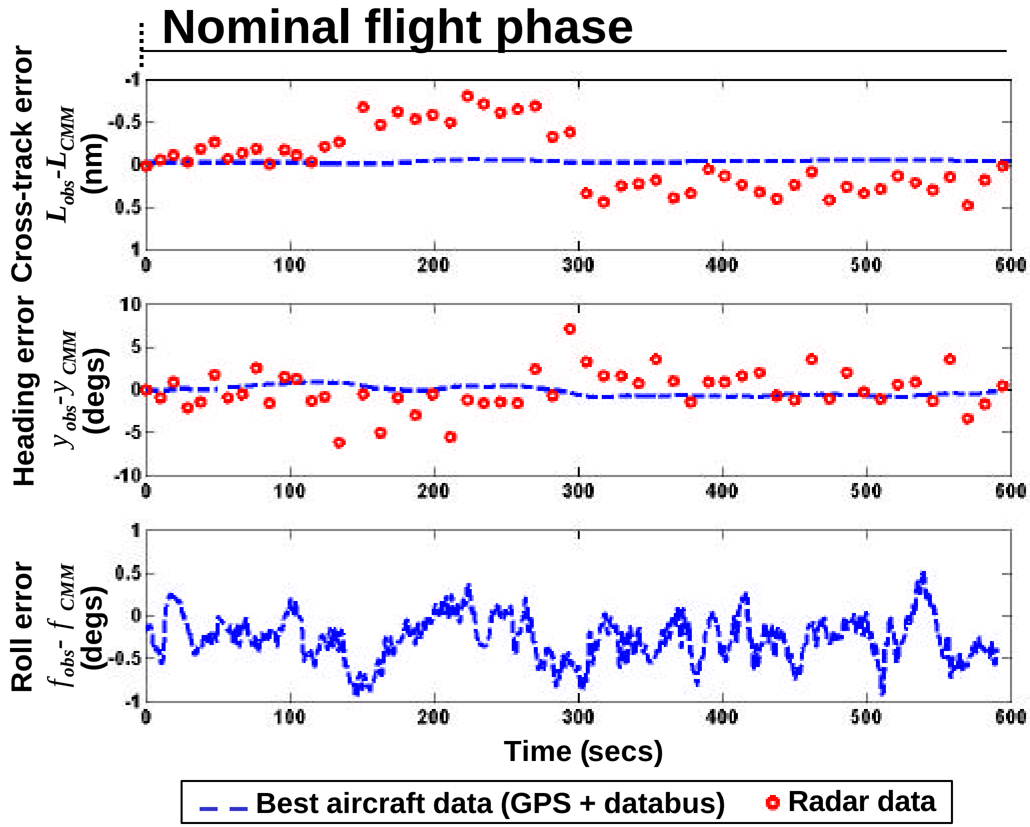
$$CR_L = WF_L \left| L_{obs} - L_{CMM} \right|$$

$$CR_{Ly} = \frac{WF_L \left| L_{obs} - L_{CMM} \right| + WF_y \left| y_{obs} - y_{CMM} \right|}{2}$$

$$CR_{Lyf} = \frac{WF_L \left| L_{obs} - L_{CMM} \right| + WF_y \left| y_{obs} - y_{CMM} \right| + WF_f \left| f_{obs} - f_{CMM} \right|}{3}$$

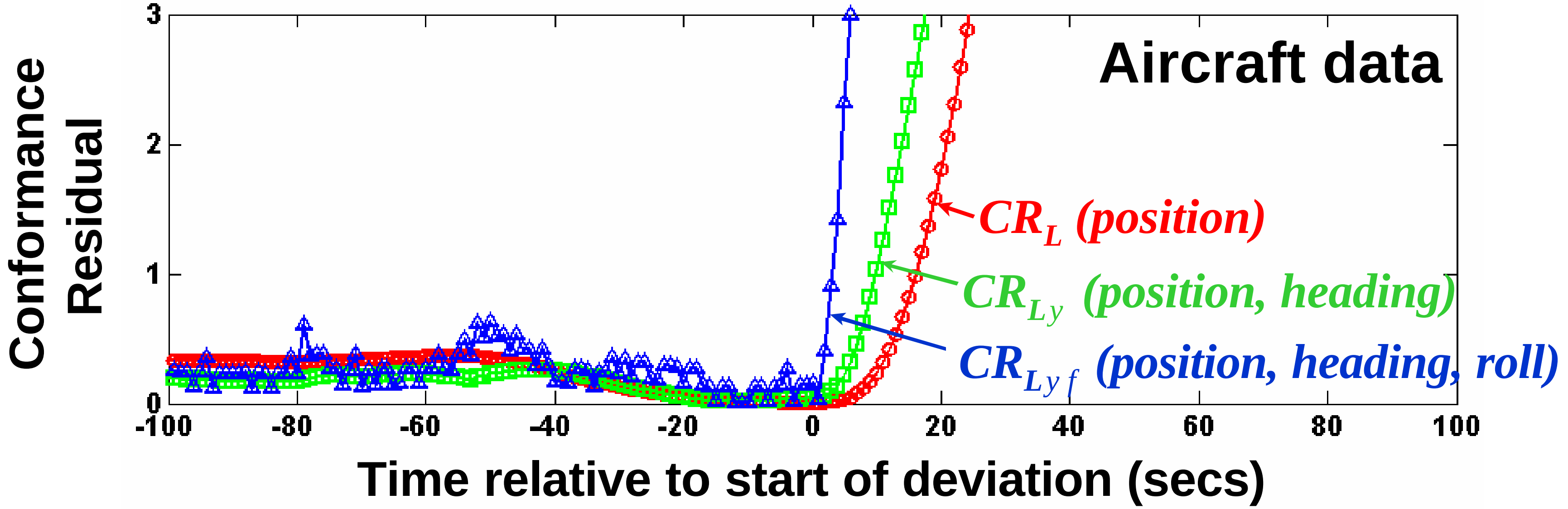
CONFORMANCE RESIDUAL WEIGHTING FACTORS

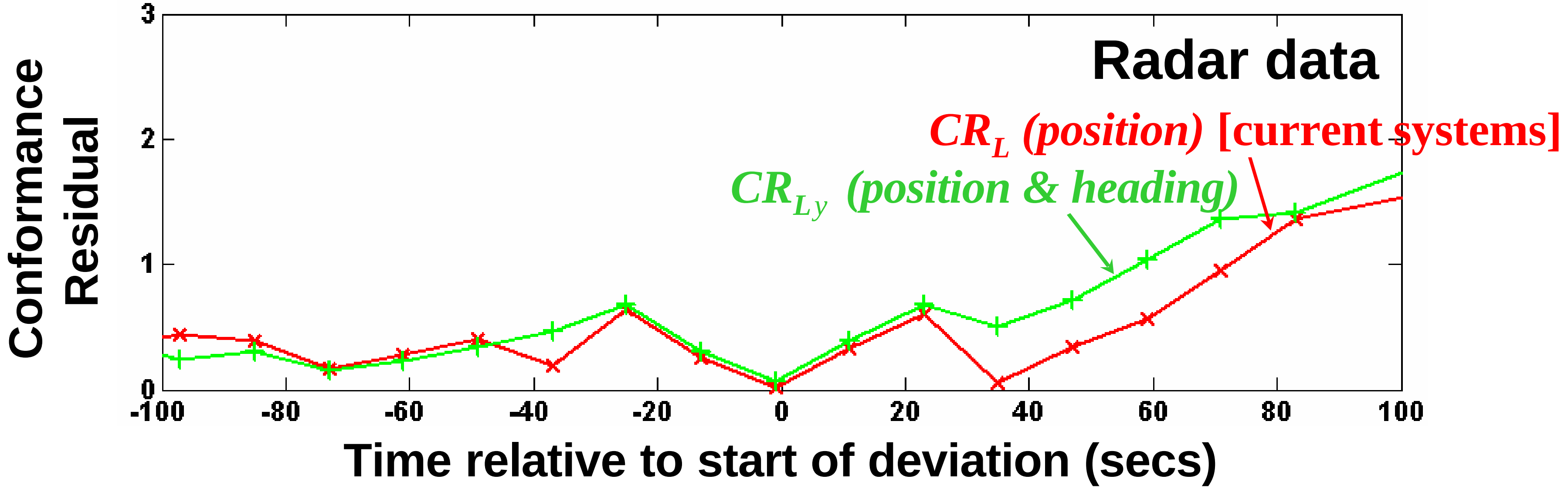
- Weighting factors on each state determined from inverse of 2s of data variations during nominal flight phase
- Consistent with RNP philosophy



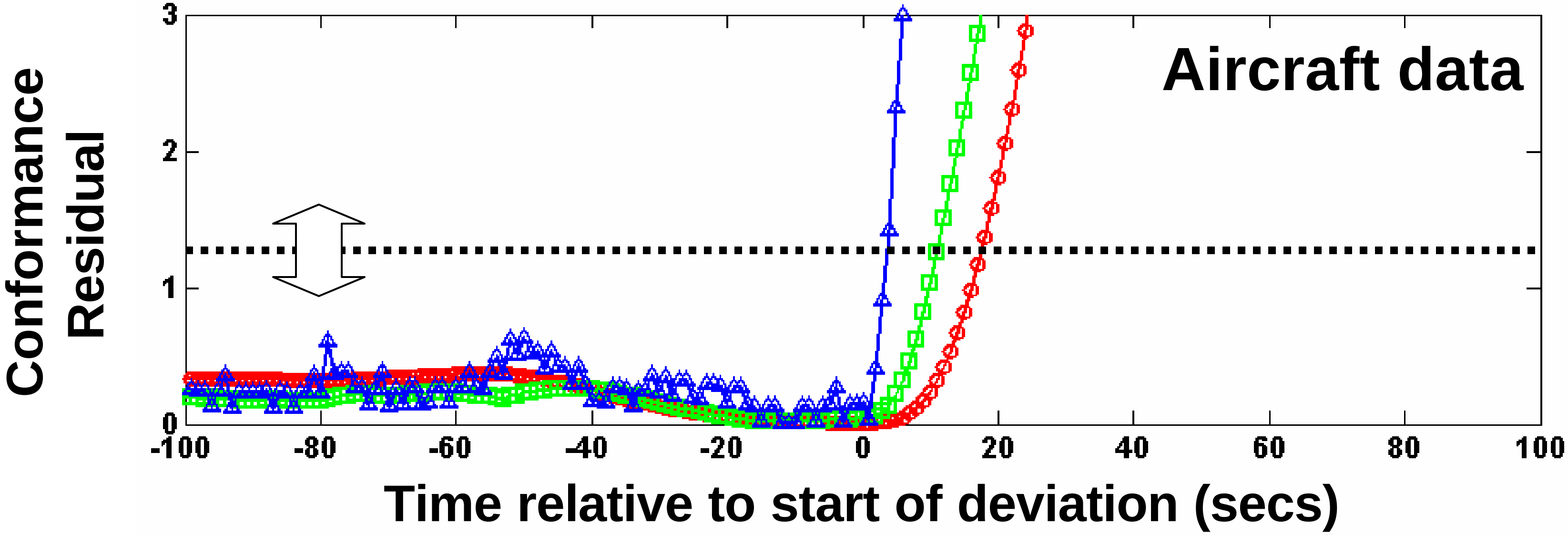
Weighting factor	Aircraft data 1/2 s	Ground data 1/2 s
WF_L	1 / 0.05 nm	1 / 0.75 nm
WF_y	1 / 1.12°	1 / 4.67°
WF_f	1 / 0.52°	N/A

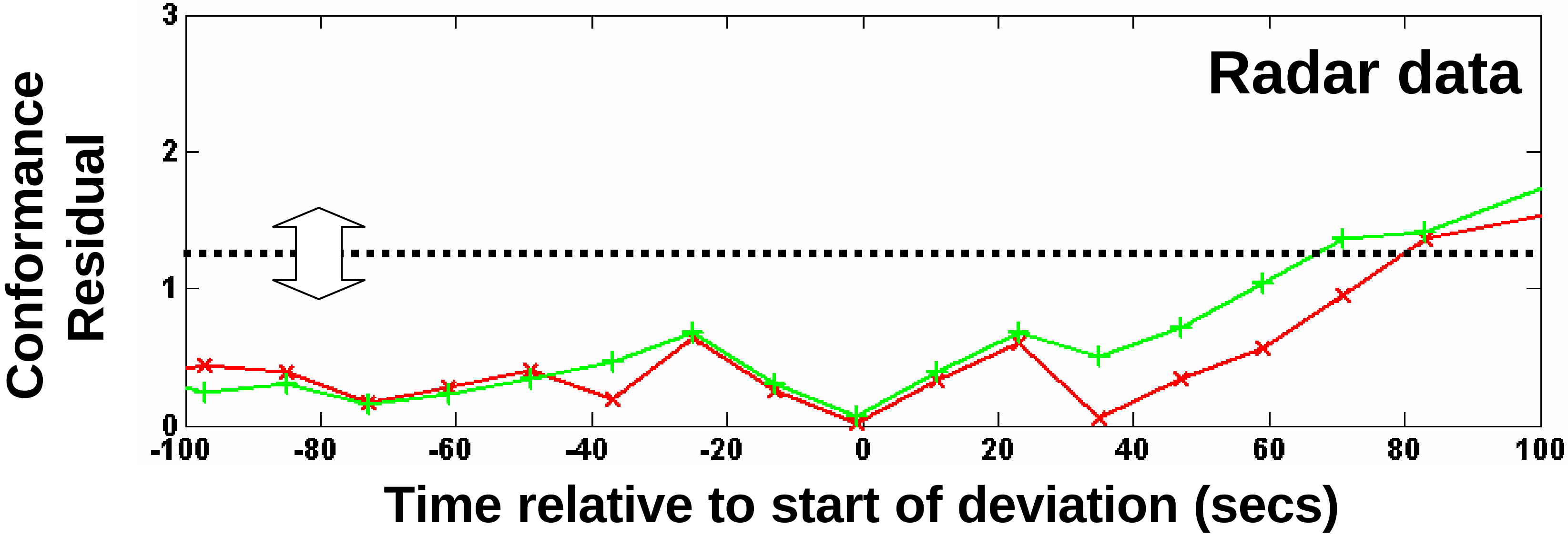
EXAMPLE LATERAL CONFORMANCE RESIDUALS



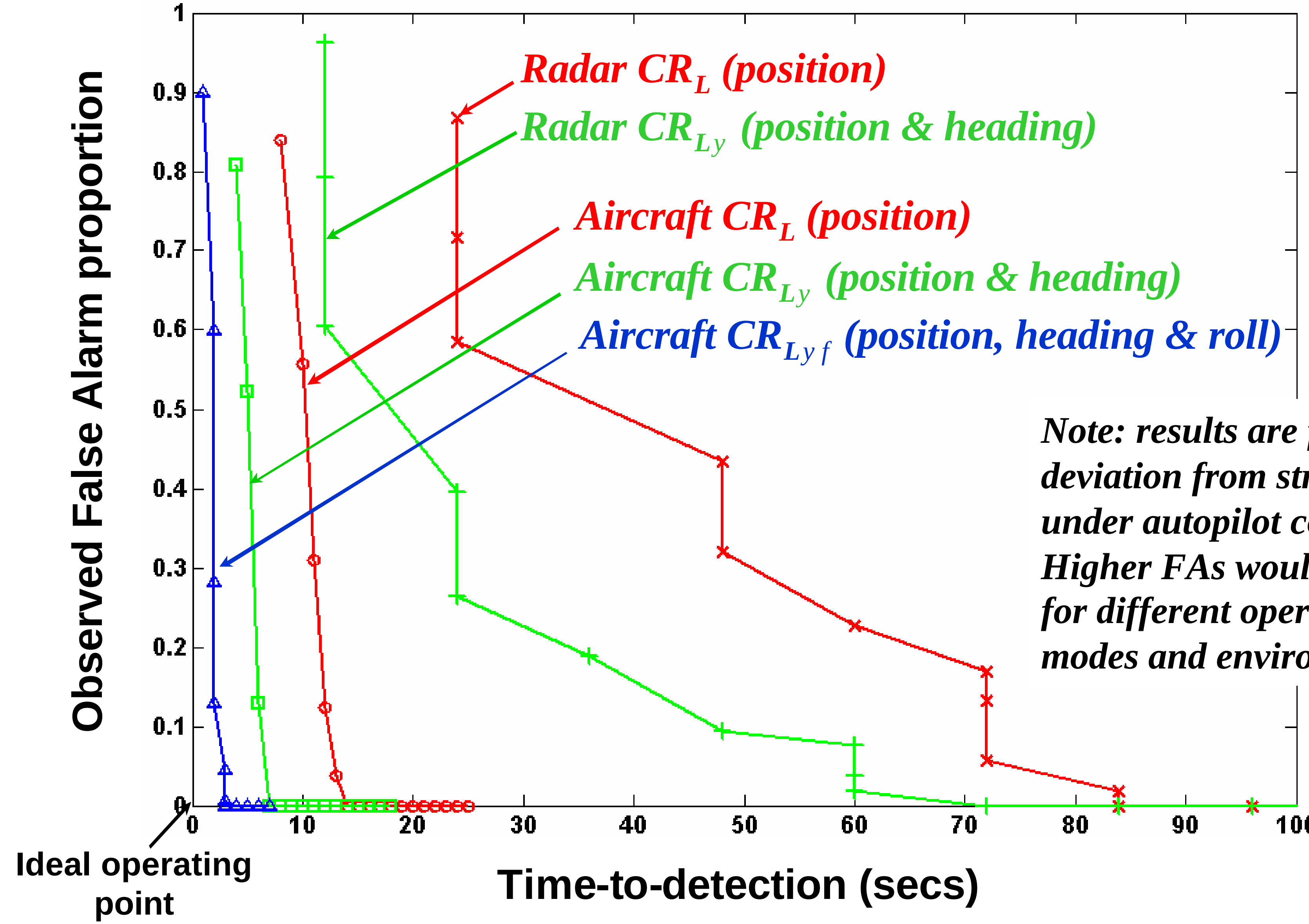


THRESHOLD-BASED DECISION-MAKING





TIME-TO-DETECTION / FALSE ALARM



Note: results are for simple deviation from straight flight under autopilot control. Higher FAs would result for different operating modes and environments.

DISCUSSION

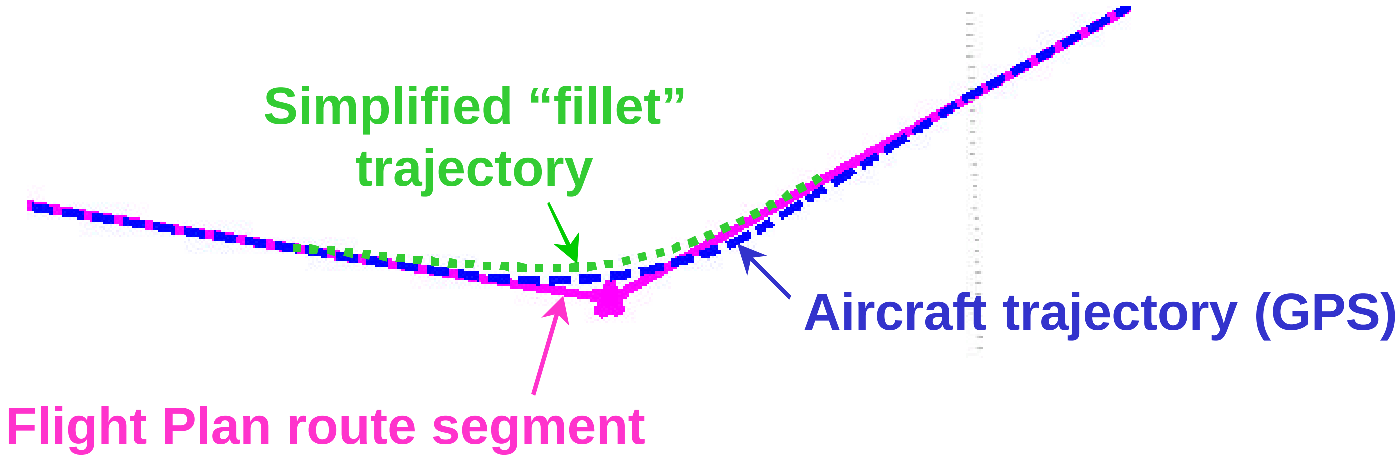
- **Significantly better performance associated with higher quality / higher update rate aircraft-based data relative to ground-based**
  - Aircraft-based curves closer to ideal operating point
  - Aircraft-based residuals allow detection times 80-90% lower than with ground-based data
- **Results suggest benefit of using higher order dynamic states in simple scenario with deviation from straight flight**
  - Provides lead over position alone
  - Expected values for higher order states easy to predict in this case
- **Use of higher order states in transition environments more difficult due to requirement to account for dynamics and added noise**
  - Discussed in next scenario

LATERAL CONFORMANCE MONITORING DURING TRANSITIONS

LATERAL TRANSITION ISSUES

- **Trajectory flown by a conforming aircraft does not follow simple approximation of Host flight plan with discrete heading change at waypoint**

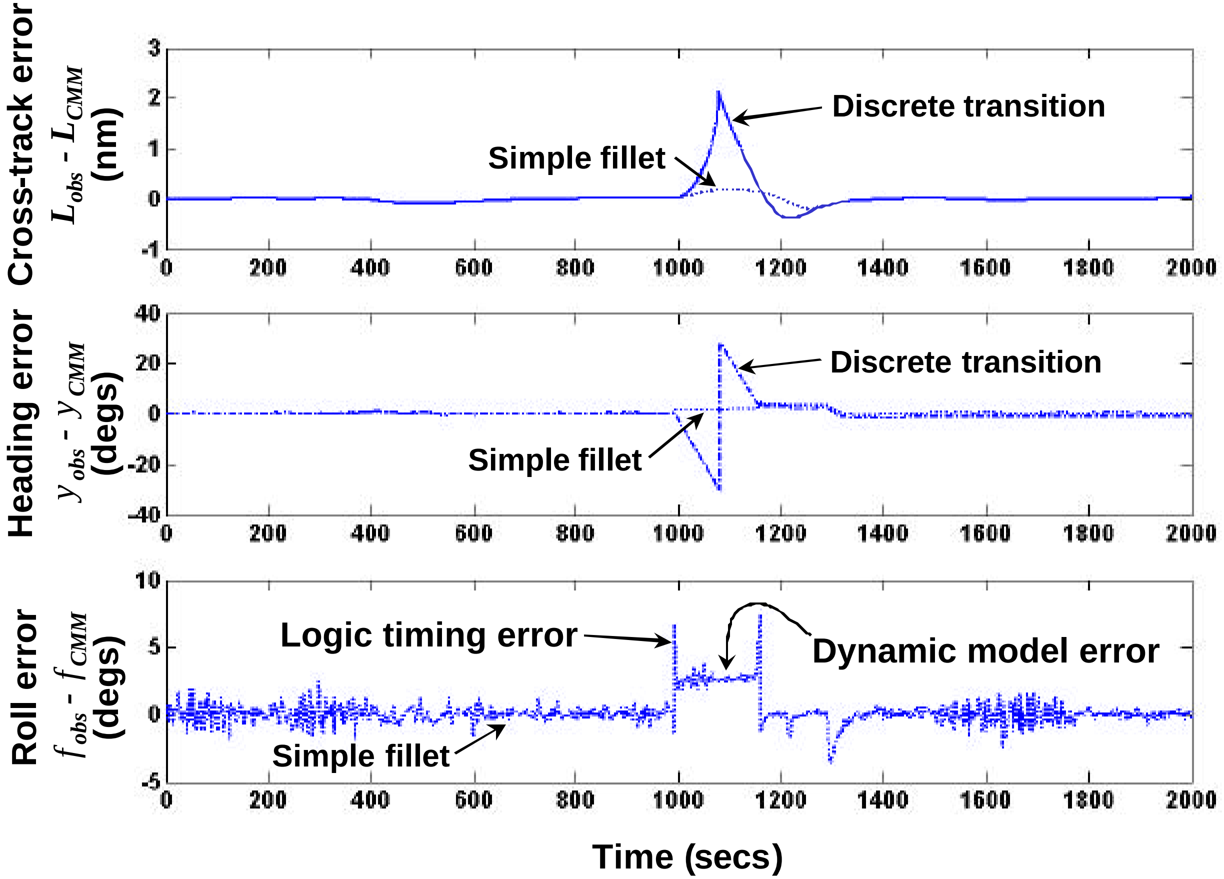
- **Need representation of aircraft dynamics to generate state expectations in Conformance Monitoring Model**
  - Expect gradual heading and roll states changes at transitions
  - Can approximate by simple “fillet” trajectory based on circular arc (as defined in RNP MASPS)



LATERAL TRANSITION ERROR STATES DURING CONFORMANCE

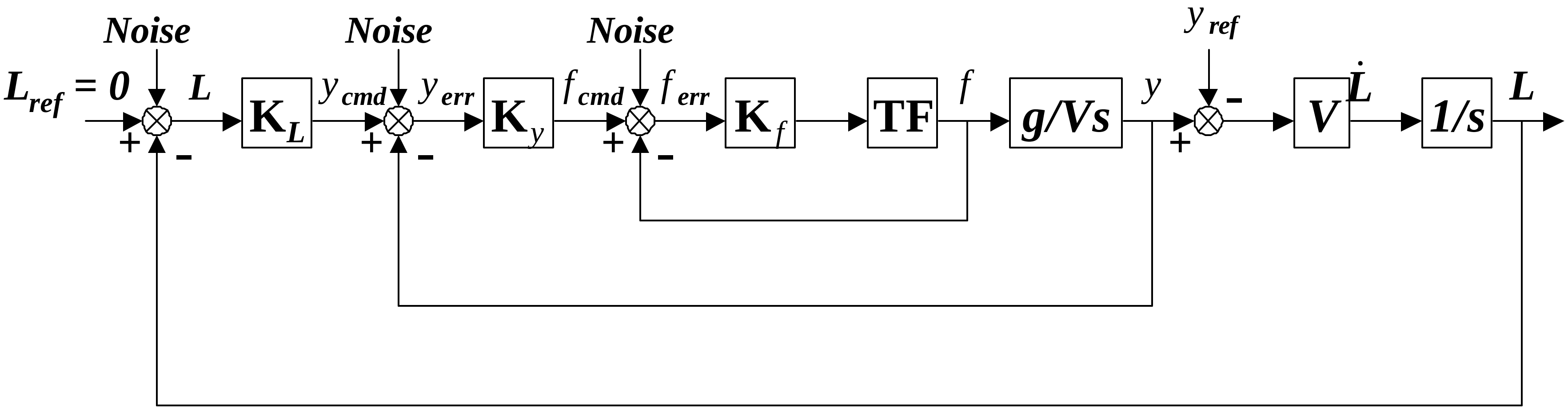
- Error states would be used to generate Conformance Residuals of the form used in the straight flight example

- Simple fillet reduces but does not eliminate residual increase at transition



FINE-TUNED DYNAMIC MODEL

- **Transition residuals could be reduced further through more accurate modeling of the aircraft dynamics and autoflight logic**



- **Possible to “fine-tune” for one flight condition of a given aircraft type, but this is not practical for ATC applications**

DISCUSSION

- **Errors in all states are significant with no filleting (discrete transition)**
- **Errors reduced but not eliminated with simple fillet**
  - Still exist due to actual dynamic model and autoflight timing mismatches
  - Mismatches more pronounced in higher order states
- **Errors could be eliminated through tuned dynamic model, but not practical in ATC**
  - Function of aircraft type, configuration, environment, etc.
- **Overall reduced ability to detect non-conformance at transitions**
  - Larger thresholds required
  - ATC procedures should not require accurate conformance monitoring at lateral transitions
- **Reduced benefit of higher order states at transitions**
  - Harder to generate expected values

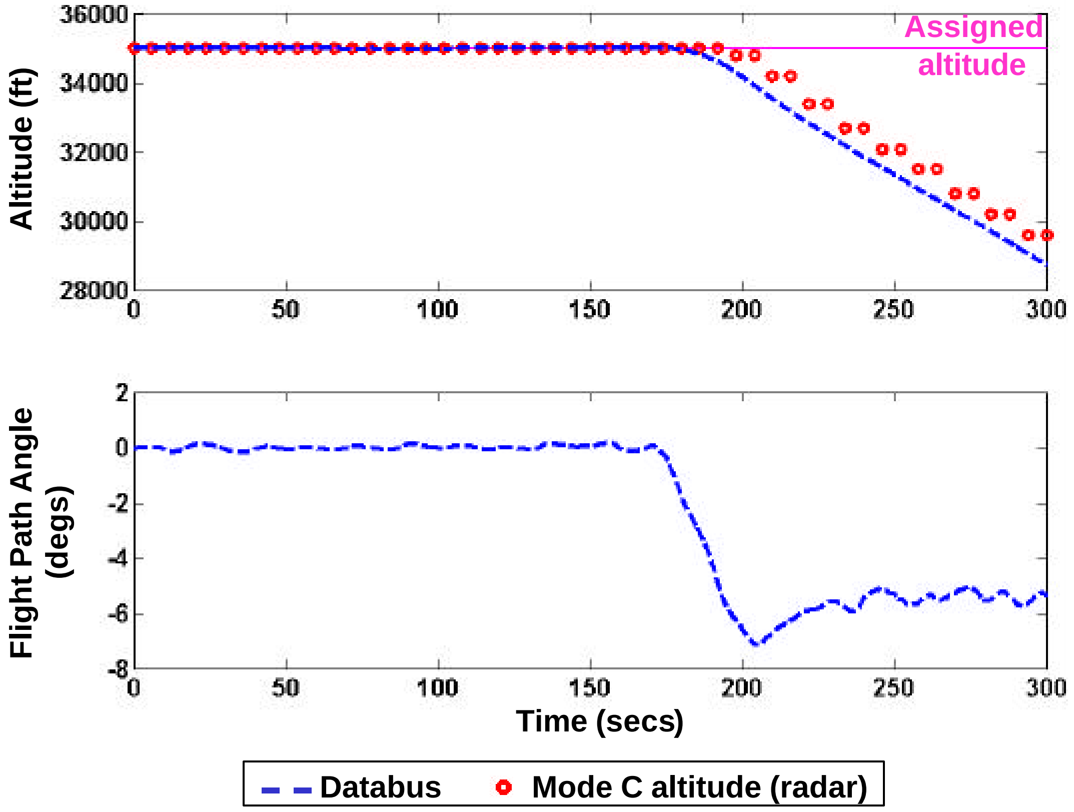
VERTICAL CONFORMANCE MONITORING DURING LEVEL FLIGHT

VERTICAL DEVIATION TEST SCENARIO

- **Vertical deviation scenario shown**
- **Comparison of conformance monitoring using:**
  - Aircraft-based altitude (A) & Flight Path Angle (g)
  - Ground-based Mode C transponder altitude
- **Conformance Residuals of form:**

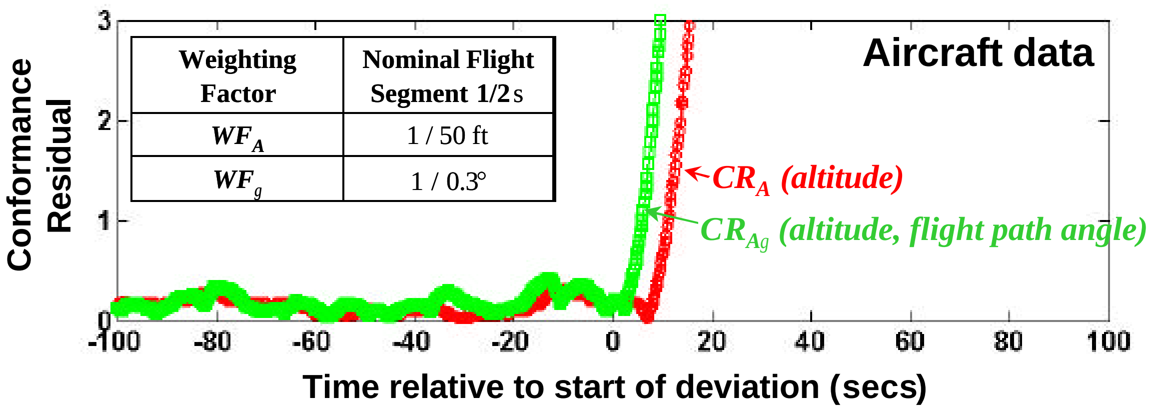
$$CR_A = WF_A \left| A_{obs} - A_{CMM} \right|$$

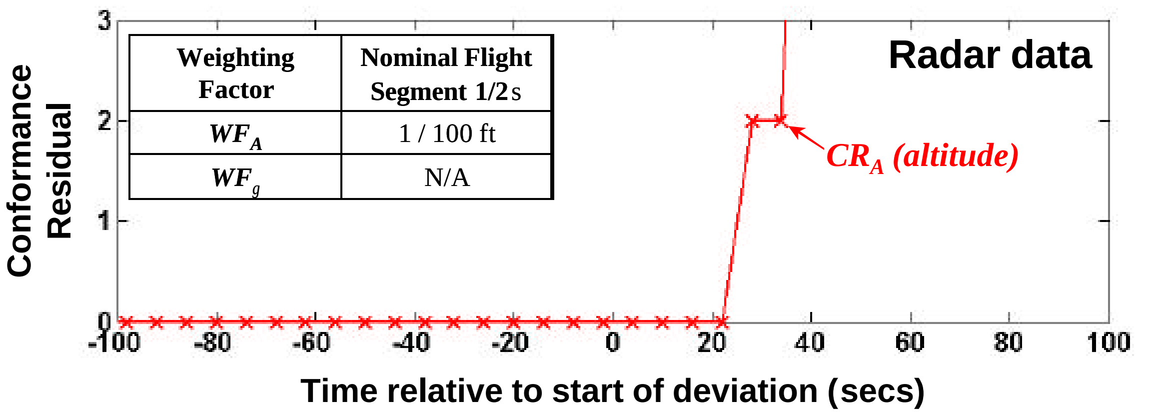
$$CR_{Ag} = \frac{WF_A \left| A_{obs} - A_{CMM} \right| + WF_g \left| g_{obs} - g_{CMM} \right|}{2}$$



EXAMPLE VERTICAL CONFORMANCE RESIDUALS

- **As for lateral case, aircraft data associated with residuals that allow faster detection than ground data**
- **Lead associated with higher order (Flight Path Angle) state in simple deviation from level flight**
  - ☐ Caveat on reduced benefit for transitions, as for lateral case

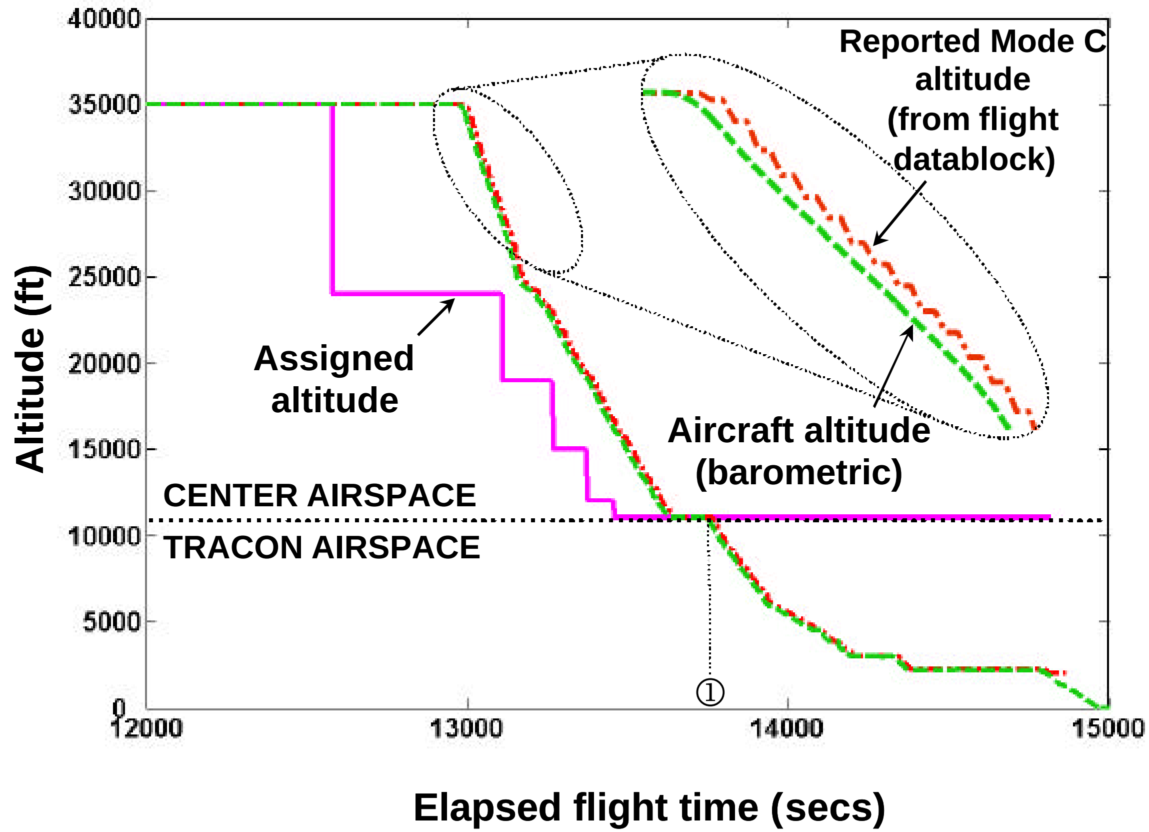




VERTICAL CONFORMANCE MONITORING DURING TRANSITIONS

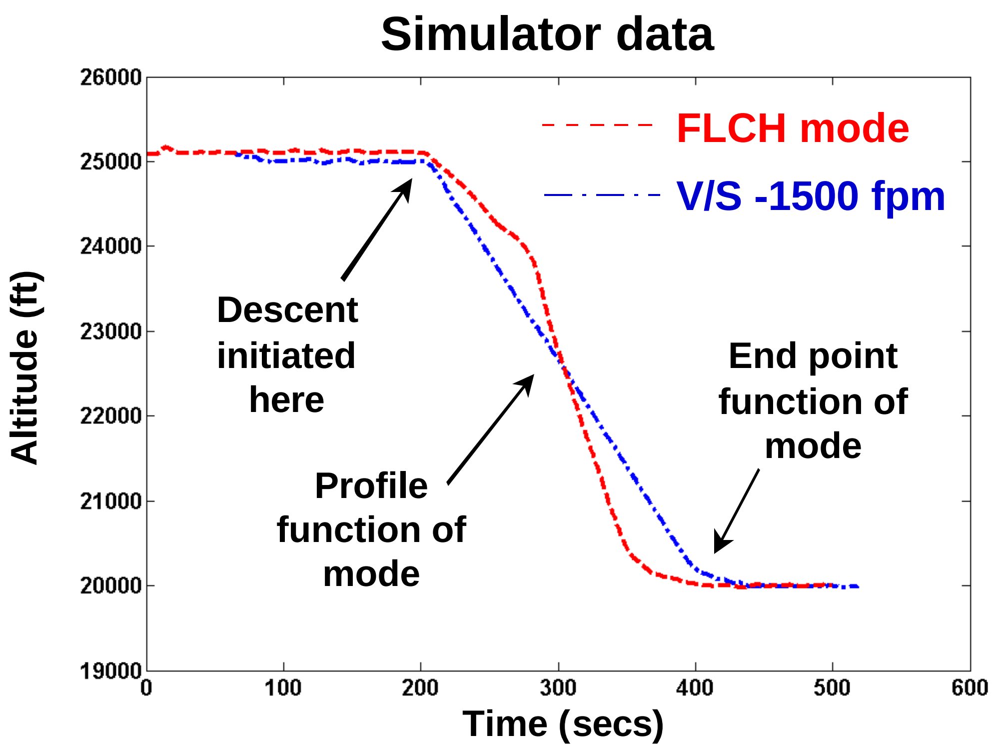
CHALLENGES AT VERTICAL TRANSITIONS (1)

- **Conformance monitoring during vertical transitions extremely challenging**
- **Poor knowledge of Conformance Basis during vertical transitions**
  - ☐ Delays often exist in descent initiation
  - ☐ Interim altitudes re-assigned before being reached by aircraft
  - ☐ Non-existent in TRACON
- **Ground (Mode C) altitude information discretized to 100 ft and lags actual altitude**



CHALLENGES AT VERTICAL TRANSITIONS (2)

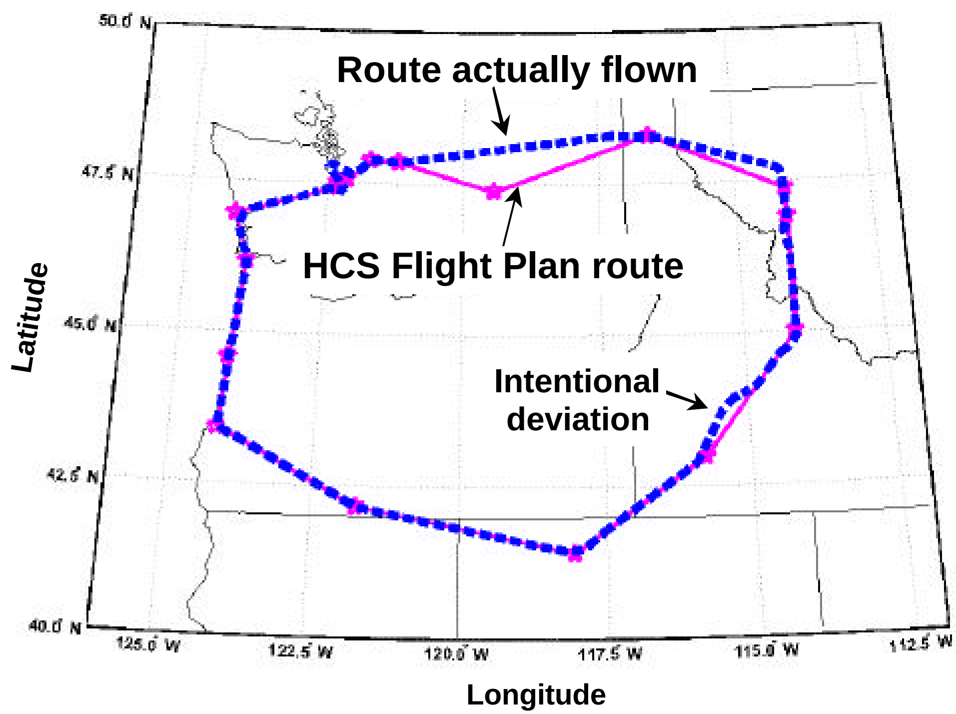
- **Even if vertical transition path has effective Conformance Basis, developing CMM is challenging due to:**
  - Multiple vertical flight modes
  - Sensitivity to aircraft configuration
    - Weight
    - Aerodynamic settings
  - Sensitivity to atmospheric properties
    - Wind
    - Pressure
- **Reduced ability to undertake conformance monitoring at vertical transitions**
  - ATC procedures should not require accurate conformance monitoring at vertical transitions



ADDITIONAL OBSERVATIONS IN OPERATIONAL DATA

SURVEILLANCE OF CONFORMANCE BASIS

- **Active flight plan in FAA Host Computer System may not reflect route flown by aircraft**
  - Amendments not always entered into automation
- **Conformance monitoring tools using automation trajectory may have out-dated or invalid information**
- **Implications for surveillance & updating of Conformance Basis in automated conformance monitoring environments**



CONCLUSIONS

- **Effective framework for investigating conformance monitoring has been developed**
  - ☐ Allows analysis of conformance monitoring approaches with different surveillance through system trades, e.g. false alarm/time-to-detection
- **Illustrated conformance monitoring during straight & level flight can be conducted relatively easily**
  - ☐ Significant benefits associated with higher accuracy/update rate data
  - ☐ Higher order dynamic states may add benefit
- **Highlighted fundamental challenges during transitioning flight**
  - ☐ Transition Conformance Basis, dynamic modeling and timing issues
  - ☐ Implications for ATC procedural design at transitions
- **Identified fundamental importance of Conformance Basis knowledge**
  - ☐ Surveillance of Conformance Basis as important as aircraft states
  - ☐ Impact on future ATC procedural design, e.g.
    - o Controller/Automation interface (voice recognition, menus, etc.)